Acta Scientiarum
http://periodicos.uem.br/ojs/acta
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v42i1.48583

CIVIL ENGINEERING

Solar fraction used in water heating systems for south Brazilian climate changes scenarios

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ABSTRACT. Solar thermal systems consist of water heating from the global solar radiation. Increasing atmospheric concentrations of greenhouse gases tend to increase the earth's surface temperature. The main objective of this work was to estimate the solar fraction obtained by means of solar heating systems for dwellings, for eight locations in the State of Paraná, in scenarios of possible climate changes projected until the end of the 21st century. F-Chart method was used to simulate the performance of solar heating systems based on the monthly average of solar radiation data, which determines the annual solar fraction or percentage of the energy demand that is covered by the solar installation. The results showed that with the impact of the climate changes, the decrease in the percentage of energy demand average that is covered by the solar installation was on average 14.3%, for both scenarios. The simulated values showed a slight decrease trend of radiation data and an increase of the solar fraction. All localities presented a characteristic seasonal behavior, with annual values of solar fraction between 82.4 and 129.8%, according to the studied localities. In relation to the monthly solar fraction, the values between November and March presented averages of solar fraction between 104 and 147.2%. But from May to August, the percentage of energy demand served by the solar installation does not reach the totality, with values between 53.6 and 99.9%. The results prove that the State of Parana has favorable climatic conditions for the installation of solar heating systems, even if it is installed for aggregation purposes, in order to reduce the electric power consumption.

Keywords: solar water heating; solar thermal; F-Chart.

Received on July 3, 2019.
Accepted on December 3, 2019.

Introduction

Brazilian cities have global solar radiation rates higher than the most developed countries such as Germany, Spain, Japan and also China. However, the use of solar thermal and photovoltaic energy in Brazil is lower than in countries that received government incentives for their use in homes (Tiepolo, Urbanetz Junior, Canciglieri Junior, & Viana, 2014; Altoé, Oliveira Filho, Carlo, Monteiro, & Martins, 2017).

According to Pereira et al. (2017), there are approximately 250,000 solar heaters installed in Brazil, totalizing more than 5 million m² of heaters, which represents only 0.6% of the total Brazilian residences. Although, the country has the third largest installed capacity of solar heating systems, but, in terms of per capita value it occupies only the 30th position, which indicates that there are opportunities for growth (Martins, Abreu, & Pereira, 2012).

Water heating accounts for 25% of the total electric energy consumed in Brazilian homes, representing a consumption of around 20 billion kWh which represents more than 6% of all the national electricity consumption (Oliveira, Ferreira, Almeida, Lobato, and Medeiros, 2008).

Thus, the replacement of the electric showerhead by a solar heater can imply savings in the electricity bill for the user, in addition to contributing to the reduction of electricity consumption peaks. On the other hand, if there is cloudy weather and there is not enough water heating, the electric shower can be used to compensate the lack of solar heating or even support.

Altoé, Oliveira Filho, and Carlo (2012) verified that the replacement of the electric shower by the solar heater with electric support reduced in average 70% the consumption of electric energy and 36% in the total consumption of electrical energy in Minas Gerais. Lenz et al. (2017) evaluated a thermosolar system and obtained from 33.7 to 53.54% of monthly efficiencies and Medeiros, Félix, Silva, Medeiros, and Braga (2014) found savings around 55% in a solar heating system compared to a conventional electrical system.

In other countries, such as India, for example, Dharuman, Arakeri, and Srinivasan (2006) evaluated an integrated model of solar water heater and achieved about 60% efficiency during the day and 40% of total efficiency and classified the collector performance as satisfactory, even during cloudy days. Nevertheless, Delač, Pavković, and Lenić (2018) obtained a 68% efficiency rate in the heating system in Croatia.

Li, Li, Wang, Hu, and Feng (2016) achieved about 78% energy savings in the hot period, in a rural residence in northwest China. Alajmi, Rodríguez, and Sailor (2018) found a reduction in energy consumption of about 64%, or 3047 kWh year^{-1}, at a residence in Portland, USA. Parker (2003) presented a 61% reduction in energy demand in the solar system when compared to the electric heater in four residences in Florida, USA.

On the other hand, Hoffman and Ngo (2018) implemented heating systems in rural communities in the Dominican Republic and obtained efficiency indices between 406 and 827%, the lowest values being reached in the month of June and the highest in January, with temperatures of air recorded between 36 and 42°C and performance results that exceeded the target temperature increase of at least 12°C.

Altoé et al. (2017) found that the maximum economic viability of the solar water heater installation is in annual solar fractions between 80 and 90%. In addition, Naspolini, Militão, and Rüther (2010) and Naspolini and Rüther (2017) found that the aggregation of solar thermal energy to the water heating for the bath in Florianópolis (SC), provides a significant annual reduction of 38 to 48% of the peak demand demanded from the utility to heat the water for the bath. While Cardemil, Starke, and Colle (2018) found a 40 to 62% reduction in peak energy consumption for the same locality.

Altoé et al. (2012) concluded that the replacement of the electric shower by the solar system with electric support caused a reduction of 70% in the electric energy consumption intended for domestic water heating and 36% in the total electric energy consumption of the residence. Medeiros et al. (2014) argued that the annual savings of the solar heating system is about 55% compared to a conventional system.

The solar heating system studied by Giglio, Santos, and Lamberts (2019), in a residential condominium in Florianópolis (SC), presented a mean of 64% reduction of peak demand, compared to an electric system, which corresponds to 0.35 kW in average reduction of peak demand and an energy saving of approximately 48 kWh month^{-1} per residential unit.

In addition, Naspolini and Rüther (2017) showed that the use of residential solar heating systems contributes to the economy between 38 and 42% in the annual cost of electric power, per consumer unit. Although the fraction of power savings per dwelling is higher in places with warmer climate, such as the North, Northeast and Central regions, the total energy savings per year is very similar for all the Brazilian regions (Martins et al., 2012).

Ma, Bao, and Roskilly (2018) found that for eight cities in the United Kingdom the solar heating system that could be installed on the roofs of the houses would supply about 38.2 to 52.6% of the total heating demands, because the required solar collector area was larger than the average roof area available in the region's standard houses.

Since in Brazil the use of electric shower to heat water is the main cause of the ‘peak of demand’ in the electricity consumption, between 6:00 and 09:00 p.m., the solar heating system presents itself as an important energy efficiency policy for Brazil, and should be considered as an effective measure to reduce energy demand at peak demand and improve the rational use of electricity, making it a relatively small subsidy that may reflect immeasurable benefits (Naspolini & Rüther, 2017; Cardemil et al., 2018; Giglio et al., 2019).

Moreover, according to Basso, Souza, Siqueira, Nogueira, and Santos (2010), there is technical feasibility in the installation of water heating equipment by solar energy in the State of Paraná, because it is possible to reach minimum temperatures of the bath water in sufficient number of days so that the electric heating is only complementary and used sporadically.

Regarding possible scenarios of climate change, it is believed that they can significantly impact the system efficiency, in this case, in a negative way, causing a small drop in the percentage of energy demand that is covered by the solar installation. Celuppi, Scapinello, Andrade, Revello, and Magro (2014) found that small increases in air temperatures promote a significant decrease in the efficiency percentage. However, even in climate change scenarios for the 21st century, Hu et al. (2016) have found in their experiments that solar energy has the potential to supply human demand both now and in the future.

The estimation of the solar fraction in function of the regionality and possible scenarios of climate change are important aspects in the evaluation of the viability of installation of integrated solar water heating systems in the residences. The popularization of solar water heaters in Brazilian homes should bring benefits to the users, due to the reduction of costs with energy consumption and can contribute to the reduction of the national demand for electric energy, benefiting the national electricity system and increasing the Brazilian energy matrix. Then, it is important that there are public incentive policies, either through laws, regulations, tax reductions, financing, awareness campaigns or research projects, that promote the adoption of solar heating systems in all types of residences.

Considering that few researches integrate global climate change with solar energy systems, this research aimed to estimate the solar fraction obtained through solar heating systems for single family dwellings, in eight localities of the State of Parana in South Brazil. Besides that, considering scenarios of global climate change projected towards the end of the 21st century were evaluated.

Material and method

Eight localities of the State of Paraná (Figure 1) were selected from climatological data of conventional meteorological stations (Table 1). According to Köppen's climate classification, the State has two types: Cfa - Subtropical climate and Cfb - Temperate climate (*Instituto Agronômico do Paraná* [Iapar], 2018).

The daily historical series of insolation and temperatures comprised a period of 31 years (1987-2017). For the simulation of climatic scenarios, the PGECLIMA_R software was used, whose daily climatic data were simulated based on the temperature increase predicted by the fifth IPCC report (Intergovernmental Panel on Climate Change [IPCC], 2014) for two scenarios.

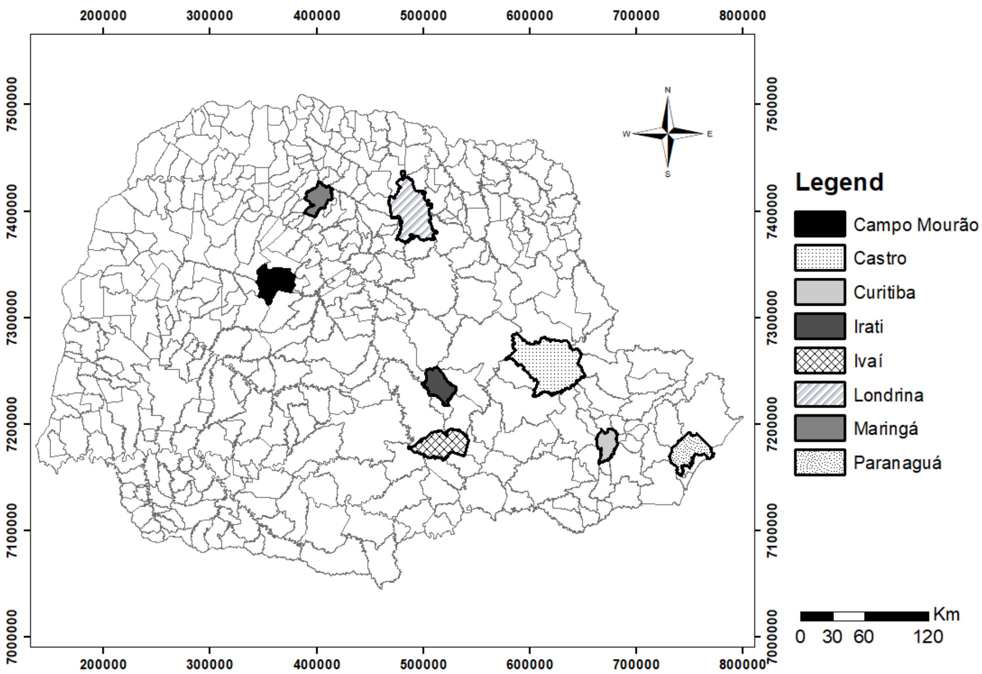

Figure 1. Selected locations in the State of Paraná.

Table 1. Geographical coordinates of selected locations.

ID	Locality	Latitude (S)	Longitude (W)	Elevation (m)
L1	Campo Mourão	-24.05°	-52.36°	616
L2	Curitiba	-24.78°	-50.00°	1009
L3	Castro	-25.43°	-49.26°	924
L4	Irati	-25.46°	-50.63°	837
L5	Ivaí	-25.00°	-50.85°	808
L6	Londrina	-23.31°	-51.13°	566
L7	Maringá	-23.40°	-51.91°	542
L8	Paranaguá	-25.53°	-48.51°	5

Based on a tendency of decrease of the thermal amplitude for the South Brazil (Marengo & Camargo, 2008; Silva et al., 2015), the simulations projected were: increases of 2.1°C in the minimum temperature and 1.3°C in the maximum temperature, for the least pessimistic scenario (C1); and increases of 5.9°C in the minimum temperature and 3.7°C in the maximum temperature, for the most pessimistic scenario (C2). It was used the software PGECLIMA_R (Virgens Filho, Oliveira, Leite, & Tsukahara, 2013).

The estimation method proposed by Chen, Ersi, Yang, Lu, and Zhao (2004; Equation 1) was adopted to predict projections for global solar radiation based on the daily temperature range and on the solar radiation at the top of the atmosphere.

$$R_G = R_A \times a \times \ln(\Delta T) + b \quad (1)$$

where:
R_G is global solar radiation;
R_A radiation at the top of the atmosphere;
'a' and 'b' are coefficients of the regression equation;
'ΔT' is the thermal amplitude (difference between the maximum and minimum temperatures).

The design of the solar system was based on the methodology of the F-Chart, which consists of the determination of the annual solar fraction or percentage of the energy demand that is covered by the solar installation.The F-chart method provides a means for estimating the fraction of a total heating load that will be supplied by solar energy for a given solar heating system (Duffie & Beckman, 1974). It was defined a hot water consumption demand of 400 L day^{-1}.

The value of the monthly solar fraction (*f*) is calculated according to Equation 2.

$$f = 1{,}029D_1 - 0{,}065D_2 - 0{,}245D_1^2 + 0{,}0018D_2^2 + 0{,}0215D_1^3 \quad (2)$$

where:
D_1 and D_2 are non-dimensional parameters presented in Duffie and Beckman (1974).

The annual solar fraction (F) is determined by means of the monthly useful energy absorbed (EU_{month}) by the solar installation for the residence's hot water production, that in turn, is expressed by Equation 3. The useful power collected is the fraction of the power that is absorbed by the collector and converted into thermal energy that is the difference between the solar energy incident on the collector and the loss to the environment.

$$EU_{month} = f \times DE_{month} \quad (3)$$

where:
EU_{month} is the monthly useful power collected, in kWh month^{-1};
f is the monthly solar fraction;
DE_{month} is the power demand, in kWh month^{-1}.

Thus, the annual solar fraction F, which can be understood as a non-dimensional relation of the energy demand attended by the system which is obtained by Equation 4.

$$F = \frac{\sum_1^{12} EU_{month}}{\sum_1^{12} DE_{month}} \quad (4)$$

The monthly data of solar fraction were simulated and segmented into four periods: Hist (1987-2017), P39 (2018-2039), P69 (2040-2069) and P99 (2070-2099). After checking the data normality by the Shapiro-Wilk test, one-way blocked analysis of variance (ANOVA) was used, at a significance level of 1%, where the month was considered as the block and the period as the main factor.

Results and discussion

From Table 2, it was observed that all localities presented statistical significance among the values of solar fraction, for C1 and C2, for both blocks (month) and for the main factor (period). The historical values presented significant positive differences in relation to all periods, in both scenarios, for all the localities, which implies a decrease of the solar fraction during the century.

With the impact of the climate change scenarios, the significant differences of f found in 2039, 2069 and 2099 were expressive in magnitude, once the decrease in the percentage of energy demand that is covered by the solar installation was on average 17.3 (14.8) in C1 and 11.3% (9.6) in C2, whereas for some localities (L3 and L4) this decrease was around 20%.

It was observed that for all localities both R_G and a f (historical and simulated in C1 and C2) presented the same variation pattern among the months of the year, although the simulated values for the periods considered showed a slight decrease trend of R_G in relation to historical values. On the other hand, in the reproduced periods of 2039, 2069 and 2099 for f this tendency pointed to an increase of the solar fraction.

In relation to the monthly solar fraction, it was observed that the values between November and March presented a similar behavior, with averages of f above 1. It was verified that from May to August, that are fall and winter months, the percentage of energy demand served by the solar installation does not reach the totality.

Table 3 presents the values of annual solar fraction (F), or solar coverage degree, for all locations, in all periods and scenarios. It was observed that, for the historical series, all localities except L2 presented values of F above 1, which represents the fullness of the annual demand for heated water, although the value of F of L2 was very satisfactory. It was observed that the simulated values showed a decreasing tendency in relation to historical values, although during the reproduced periods of 2039, 2069 and 2099 this tendency was shown to be increasing.

It was verified that, in spite of the decrease observed in relation to the historical period, the localities L1, L6 and L7 generally obtained values of F greater than 1 in C1 and C2. Although the other locations (L2, L3, L4, L5 and L8) did not reach full service, annual percentages were reached above 82%, values considered compatible with the climate of the localities and the expected seasonality of solar heating systems.

In general, for all the localities, it was observed that the simulated solar fraction values showed a decreasing tendency over the reproduced periods of 2039, 2069 and 2099, in relation to historical values. This fact can be explained by the method of calculation of the solar fraction that uses the global solar radiation data. Once it was verified that the estimated values of R_G from the simulated maximum and minimum temperatures also showed a tendency to decrease, this behavior could be attributed to the model used to estimate the R_G of Chen et al. (2004), which is based on the daily thermal amplitude (ΔT).

Table 2. Comparison of averages of the monthly values between the historical and simulated periods

ID	ANOVA		Comparision of averages			
C1	p-Block	p-Treat	Hist	P39	P69	P99
L1	0.0000	0.0000	1.2521a	1.0462c	1.0584bc	1.0747b
L2	0.0000	0.0000	0.9692a	0.8510b	0.8653b	0.8673b
L3	0.0000	0.0000	1.1159a	0.8765b	0.8932b	0.8814b
L4	0.0000	0.0000	1.1120a	0.8933c	0.9801b	0.9084c
L5	0.0000	0.0000	1.1711a	0.9618c	0.9732bc	0.9879b
L6	0.0000	0.0000	1.3006a	1.1174c	1.1355bc	1.1517b
L7	0.0000	0.0000	1.3212a	1.1274b	1.1414b	1.1517b
L8	0.0000	0.0000	1.1444a	0.9398c	0.9600bc	0.9773b
L8						
L1	0.0000	0.0000	1.2521a	1.0669c	1.0899c	1.1268b
L2	0.0000	0.0000	0.9692a	0.8629c	0.8902c	0.9258b
L3	0.0000	0.0000	1.1159a	0.8918c	0.9050bc	0.9214b
L4	0.0000	0.0000	1.1120a	0.8974d	0.9236c	0.9502b
L5	0.0000	0.0000	1.1711a	0.9733c	1.0226b	1.0537b
L6	0.0000	0.0000	1.3006a	1.1346d	1.1701c	1.2147b
L7	0.0000	0.0000	1.3212a	1.1463c	1.1809bc	1.2160b
L8	0.0000	0.0000	1.1444a	0.9618d	1.0204c	1.0777b

Note: Values followed by lower case letters do not differ statistically from each other at the 1% level of significance.

Table 3. Annual solar fraction (non-dimensional values) for all locations in all periods and scenarios.

Scenario/Period		C1			C2		
ID	Hist	P39	P69	P99	P39	P69	P99
L1	1.223	1.010	1.019	1.036	1.029	1.048	1.076
L2	0.942	0.824	0.836	0.836	0.835	0.857	0.885
L3	1.089	0.850	0.865	0.853	0.863	0.873	0.889
L4	1.082	0.863	0.946	0.874	0.865	0.887	0.909
L5	1.140	0.926	0.938	0.949	0.937	0.979	1.004
L6	1.274	1.083	1.099	1.113	1.097	1.129	1.170
L7	1.298	1.096	1.107	1.114	1.113	1.141	1.171
L8	1.109	0.898	0.916	0.931	0.919	0.967	1.015

Since the projections of the climatic scenarios caused the decrease of this amplitude, this tendency incorporated in the model caused the reduction of the values of solar radiation that, consequently, caused the decrease of the solar fraction. Similarly, Bierhals, Pereira, Brazil, and Rossini (2017) found that, for the State of Rio Grande do Sul, climate scenario models have shown that global solar radiation values tend to decline to 60% of the year through 2100. Furthermore, Huber et al. al. (2016) concluded that global solar radiation in the future (2035-2039) is likely to be reduced by comparing historical values (1995-1999).

It is important to note that the highest values of solar fraction verified, refer to the months between October and March, coinciding with the spring and summer seasons, when the sun's rays illuminate the southern hemisphere more. With similar justification, the lowest values refer to the months from April to September, belonging to fall and winter, when the days are shorter in the southern hemisphere and the solar rays have lower intensity, due to the apparent movement of the Sun in relation to the Earth and due to the solar declination.

From Figure 2 and 3, it was observed that in general, all the localities presented a characteristic seasonal behavior, with the total and surplus attendance of the system in the seasons corresponding to spring and summer, whereas in the months of fall and winter, the demand was not fully satisfied by the system, being that this behavior is compatible with the seasonality predicted in solar energy systems.

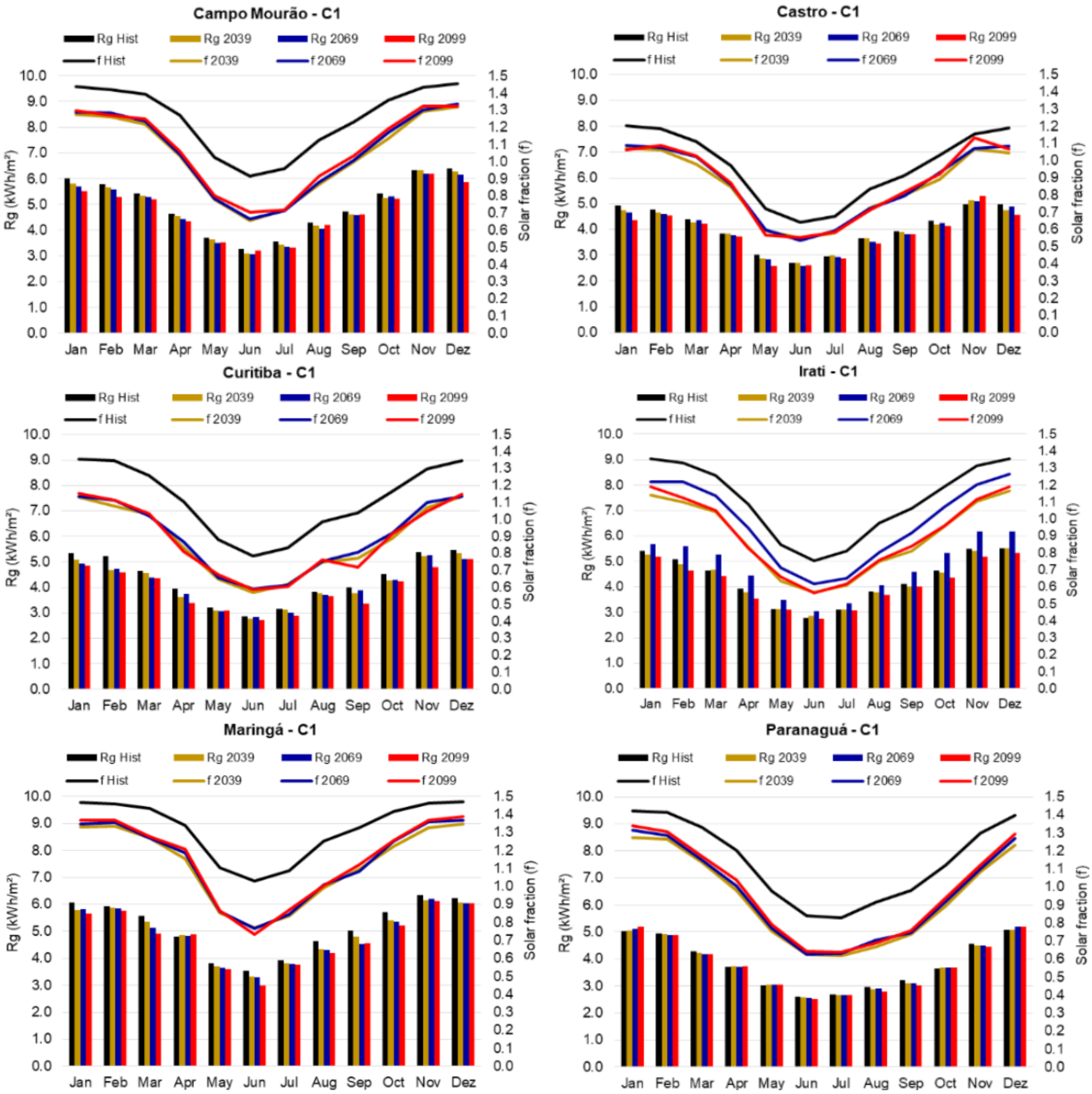

Figure 2. Global solar radiation (R_G) and solar fraction (f) of the system in the historical period and until 2099 in C1 scenario for all localities.

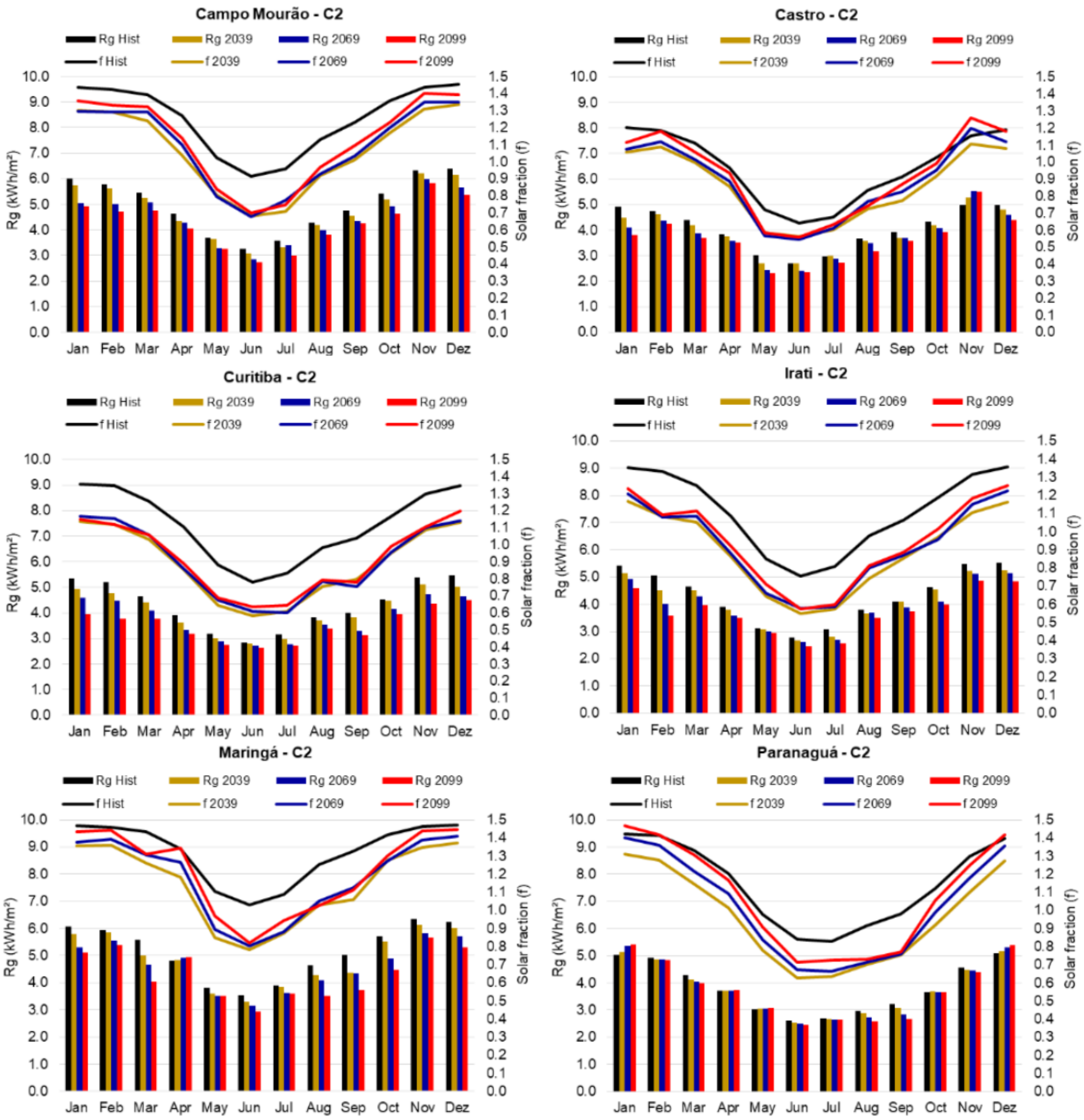

Figure 3. Global solar radiation (R_G) and solar fraction (f) of the system in the historical period and until 2099 in C2 scenario for all localities.

Similarly, Barbosa and Carvalho (2018) verified that the daily energy of the solar heating system, installed in the city of João Pessoa (PB), is not sufficient to meet the demand in five months of the year (from May to August). For this locality, this period is the one with the lowest incidence of solar radiation, which results in a smaller amount of collected useful energy and consequently of stored energy. In another research for this locality, Medeiros et al. (2014) found that the solar fraction calculated in most of the months was higher than 0.65, and only in June, July, August and November was less than 0.60, with an annual average of 0.65 and monthly fractions between 0.47 (July) and 0.87 (February).

In other places in Brazil, such as Florianópolis (SC), Cardemil, Starke, and Colle (2018) obtained solar fractions in the range from 0.5 to 0.9, with July being the worst recorded month, whereas the months of February and December were the only ones that reached values of f above 0.8. Sinigaglia, Seiboth, Michels, Lovato, and Jahn (2016) obtained annual solar fraction with an average value of 1.076, that is, 107.6% of the annual demand served in the northwest of the State of Rio Grande do Sul. In addition, the system presented values of monthly solar fraction in the interval between 0.40 (June) and 1.72 (January). In May, June, July, August and September, the collector would not be able to supply energy demand.

In general, the solar fraction can be understood as an efficiency metric of the solar water heating system. Therefore, all the studied localities had annual efficiency values above 80%. Basso et al. (2010), evaluated a prototype of a solar heating system in the city of Cascavel-PR and found average efficiency above 80% in the winter months, while Celuppi et al. (2014) obtained approximate efficiency of 65% in their experiments in the city of Chapecó, Santa Catarina State.

It is important to highlight in this research that the solar collectors installed in the hypothetical residences would occupy an area of approximately 8 m^2, that is, less than 10% of the available area of the considered roof. It should be noted that, in order to obtain higher efficiency values, more collectors could be installed. However, it was decided to keep the same number scaled for historical values.

Conclusion

The modeling applied showed annual solar fraction values between 82.4 and 129.8%, which are similar to those found in other Brazilian locatilities, and proves that the country has favorable and satisfactory climatic conditions for the installation of solar heating systems. Even though in South Brazil, the winter months do not reach full service, the monthly solar fractions found contribute to the reduction in the consumption of electric power, since these systems can function as aggregators in the residence and do not, necessarily, operate isolatedly.

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